Excitation and Evolution of the Quasi 2-Day Wave Observed in UARS/MLS Temperature Measurements

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Abstract

The quasi 2-day wave is known as a strong dynamic perturbation occurring usually after solstice in the middle and upper atmosphere. The excitation mechanism of this transient wave is discussed for years but no clear answer has been attained. In this paper, propagating characteristics of the 2-day wave are studied based on 8-month temperature measurements from the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS). The studies are focused on the wave events that happened in January 1993 and in July/August 1993. The data suggest that winter planetary waves could be responsible for triggering the summer 2-day wave through long penetration into the summer stratosphere. A connection is evident in the evolution of the wave amplitude between the summer 2-day wave generation and winter wave penetration. The data also suggest that the enhancement of the wave amplitude is a result mixed with a local unstable wave and a global normal-mode Rossby wave.

Introduction

The quasi 2-day wave is a global westward traveling oscillation often observed in the middle and upper atmosphere during the months of January/February and July/August. The 2-day oscillation has been found in mesospheric wind measurements over 80-100km at a number of ground-based radar stations (for example, Müller and Kingsley, 1974; Craig and Elford 1981; Tsuda et al., 1988) as well as in upper stratospheric rocketsonde winds (Coy 1979). Satellite temperature and wind measurements (Rodgers and Prata, 1981; Burks and Leovy, 1986; Wu et al. 1993) are able to provide a global view of the phenomenon and associate it with zonal wave 3-4 structures. The 2-day wave appears to be one of the strongest perturbations to atmospheric dynamics and has several interesting features. It occurs intermittently with a lifetime of 10-30 days, and the wave events usually peak one month after solstice at the mid-latitudes summer hemisphere. The wave period varies from 1.8 to 2.3 days with larger frequency variability in July/August events.

Two mechanisms have been proposed to explain the wave excitation. One is known as the normal-mode theory (Salby, 1981) which interprets the 2-day oscillation as a manifestation of the (3,0) Rossby normal mode. In the realistic atmosphere, a resonant normal mode may be distorted in shape due to non-uniform mean wind structures and easily triggered. A small perturbation such as atmospheric instability and breaking planetary waves may excite a global normal-mode response if the atmospheric conditions are favored. Atmospheric viscosity, in the meanwhile, is the damping mechanism that prevents normal modes from further growth. Another explanation for the 2-day wave emphasizes the role of the baroclinic instability above the summer easterly jet (Plumb

1983). According to this theory, the 2-day wave is one of fast growing unstable modes due to the atmospheric instability and the enhancement is localized in the unstable zones. A perturbation may grow widely in a short period of time if it matches an unstable mode in wavenumber and frequency.

It also possible that the 2-day wave exists as a combination of normal and unstable modes. As suggested by Randel (1994), the observed wave structures, on one hand, agree well with normal mode calculations showing an expected (3,0) structure in the summer hemisphere and a consistent phase relation across the two hemispheres. On the other hand, the episode of the summer 2-day wave is well correlated with the local instability signature in the 5-year observations. The match of the (3,0) normal mode and unstable waves in frequency and wavenumber makes the 2-day wave difficult to distinguish between the two components. In fact, the coupling of the normal mode and baroclinic instability enables the 2-day wave more readily to be excited near a solstice period. It has been suggested that the forcings leaking from the winter into the summer hemisphere may be responsible for the initial triggering (Tsuda et al., 1987; Craig et al., 1980).

In this paper, we present more evidence of excitation and evolution of the 2-day wave observed in the temperature measurements with the Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS). Evolution of the 2-day wave in a high temporal resolution is obtained to study detailed cause-and-effect relation of the propagating disturbance. Behaviors of the wave propagation are found to be consistent with the suggestion that the 2-day wave is composed of both normal and unstable modes during its development. A connection between the summer 2-day wave and the winter wave is evident in the MLS data, which may reveal a signature of the winter wave leaking into the summer hemisphere and triggering the summer 2-day wave.

Data

The data analyzed here are obtained with special research algorithms developed by the MLS science team for improving temperature and pressure retrievals. The MLS, in operation since 12 September 1991, is a remote-sensing instrument to simultaneously measure molecular abundances (0_3, CLO, H_20, and HNO_3), temperature and pressure in the middle atmosphere (Waters, 1993; Barath et al., 1993). Temperature and pressure are retrieved from the radiance measurements of 0_2 microwave thermal emissions near 63 GHz of which line spectrum is resolved into 15 channels. in the standard MLS products, currently available for public, temperature is retrieved using the MLS Version 3 (V3) algorithm at 6 pressure levels from 22 mb to 0.46 mb. With some modifications, temperature is retrieved at 10 pressure levels in the new algorithms including 46, 0.22, 0.1 and 0.046 mb.

The basic principle of temperature retrieval is the same in both the new and standard algorithms (Fishbein et al., 1995). The major differences, which lead to better results for temperature, are in the treatments about background emissions and radiance measurements near the line center. The new temperature results, although still preliminary, are improved in several aspects: (1) The systematic bias due to background emissions is greatly reduced. There was a - 1K systematic variation that synchronizes the UARS yaw cycle in the V3 temperature. A better model is applied in the new algorithms to remove the non-atmospheric contributions, reducing the bias to less than 0.3 K. (2) Temperature at 0.22, 0.1 and 0.046 mb is being retrieved for scientific uses. The temperature information at these levels comes primarily from the radiance close to the line center which is measured with three channels. The three center channels are excluded in the V3 software for concerning possible contamination due to Zeeman splitting of the earth's magnetic field. However, in the new algorithms we take advantage of the fact that the saturated radiance is a weak function of the Zeeman effect, and include the three-channel radiance measurements for the temperature retrieval, As a result, we obtain some useful temperature measurements at higher altitudes. (3) In the new algorithms, temperature retrieval is coupled with pressure retrieval in a vector format. The vector scheme improves both pressure and temperature retrievals at high altitudes because it prevents retrieval errors from propagating to low altitudes as inherent in the onion-peeling type of retrievals employed by the V3 software, (4) The new temperature product is now independent of the NMC analyses. Instead of relaxing to the National Meteorological Center (NMC) data, the new product is constrained to a UARS climatology when there is no temperature information from the radiance measurements. Therefore, the new product is more valuable for applications in data assimilation,

The bias due to the earth's magnetic field is present in the new temperature data and requires special care because the algorithms have not accounted for the Zeeman splitting effect. Temperature may be retrieved up to -0.005 mb from the MLS radiance measurements if the Zeeman effect is accurately calculated. However, at the present time, the modeling efforts are limited to a few simple calculations which are not enough to deal with complicated magnetic field orientations. Given the existing forward model calculations, temperatures up to 0.022 mb may still be retrieved if saturated radiances in the center channels are used. Such retrieval, avoiding sophisticated computation about the magnetic effect, may produce some scientifically useful results, but additional errors need to be quantitatively assessed. The errors are estimated and listed in Table 1 for selected pressure levels. Since the effects of the magnetic field is approximately stationary for the MLS, the introduced errors expose less serious contamination to the study of fast moving waves than the study of slowly moving waves, and waves 2 and **3** are less affected than wave 1 and mean components. The confidence level for the 2-day wave amplitudes obtained in this study is about 0.5 K at heights below 0.46 mb and 1 K above that height.

TABLE 1

	Accuracy		Precision in Temperature (K)			
				Magnetic Field Effects		
Pressure level (mb)	Pressure (meters)	Temperature (K)	Diurnal & Yaw-cycle	Mean	Wave 1	Wave 2
0.046	70	5	<0.3	8	8	<2
0.1	40	6	<0.3	5	5	<1
0.22	30	4	<0.3	2	2	<0.5
0.46	20	1.5	<0.3	<0.5	<0.5	0
1	20	1	<0.3	0	0	0
2.2	30	0.8	<0.3	0	0	0
4.6	40	0.6	<0.3	0	0	0
10	60	0.7	<0.3	0	0	0
22	120	1	<0.3	0	0	0
46	**180**	**2**	<0.3	0	0	0

The MLS sampled latitudes range from 34° in one hemisphere to 80° in the other and two solar local times are sampled at a given latitude circle. The spacecraft makes 10 yaw maneuvers per year, allowing views of the polar regions alternately. There are 15 orbits per day and about 90 profiles per orbit. The data during 30 November 1992-17

September 1993 are analyzed and two solstice periods are covered with continuous observations.

Wave Spectra

The MLS temperature data, gridded in latitude and pressure level, are subject to spectral analysis to extract zonally propagating wave perturbations. A wave spectrum, which is defined here as the amplitude response at a given frequency and wavenumber, is calculated using a least squares fitting technique (Wu et al, 1995). Aliasing is also examined for the different sampling patterns at various latitudes. For UARS, there are enough samples to resolve a wave 3 structure such that the 2-day wave is generally not aliased by other major planetary waves. However, in the high-latitude stratosphere winter, planetary waves are so strong and rich in spectrum that the leakage of spectral power may not be negligible. In most cases, the 2-day wave is a well-defined spectral component and easily resolved.

Figure 1 presents the wave spectrum at a latitude of 20°S and a pressure level of 0.46 mb for the period of Jan. 10-30, 1993, when the 2-day wave, a westward traveling oscillation, sharply peaks at a period of -48h and zonal wavenumber 3. The 48h period derived from the MLS temperature data is slightly different from 51 h reported by Rodgers and Prata (1981) for the temperature measurements in January 1973 but agrees well with the NMC observations (Randel, 1994). The 2-day wave period, as suggested by normal mode calculations (Salby, 1981; Hagan et al., 1993), may vary slightly if the structure of mean flow changes and multiple spectral components may also be present. Nevertheless, these calculations suggest that the prominent spectral component of the January event should be close to the 48h. The 2-day wave may not be easily identified from a map of temperature anomaly because as seen in Figure 1, other planetary waves are also present, for example, the diurnal tide, a westward propagating 10-day wave, and the stationary wave 1.

Figure 2 is the wave spectrum at a latitude of 20°N and a pressure level of 0.1 mb for the period of June 18-July 7, 1993. This is a much weaker event than that in January, and consists of two equally important spectral components. One component peaks at a period of -50h and zonal wavenumber 3 while another can be identified at a period of -45h and zonal wavenumber 4. These values are somewhat different from 58h and 55h found in the NMC temperature data (Randel, 1994) but there is consistency showing that the shorter period is also associated with the larger wavenumber. Some aliases are also present in the spectrum because this sampling pattern is different from the case in January 1993. The weaker amplitudes, located at (wavenumber, period) = (-3, -0.49) and (-2, 0.53), are respectively the aliases of the 2-day wave components at (4, 0.53) and (3, 0.48). Aliasing arises because two nodes sampled at this latitude circle are too close together in local time. Since the aliasing is not mutually equal in amplitude, we are able to distinguish the aliasing and aliased components. Multiple wave components were also observed in mesospheric radar winds during the month of July 1991 (Harris and Vincent, 1992), where periods of51 h and 44 h were specified.

The 2-nay Wave in January 1993

The 2-day wave amplitudes and phases are extracted at the two prominent frequencies, i.e., (3, 0.5) and (4, 0.53), using the same least squares method. A frequency filter of 0.25 day^{-1} is chosen for a fine temporal resolution in time series. For the January event, the time series of the wave amplitudes at (3, O. 5) and (4, O. 53) are shown in Figures 3 and 4 respectively. In order to investigate detailed generation and evolution processes, the 4-day resolution is desired so that the direction of wave progression can be resolved precisely. As discussed later, with the fine resolution, we are able to understand, to a better extent, cause-and-effect relations among the 2-day wave, instability effects and other planetary waves.

The time series in Figure 3 shows the very early stage of the 2-day wave generation during late 1992 and early 1993. A precursor can be seen at all levels around 10 December 1992 in the northern hemisphere, which gathers strength through the winter and eventually spreads to the equator with increasing height. A second strong disturbance in the northern hemisphere occurred near the end of December, which shows a similar radiating pattern into the southern hemisphere. These transient perturbations in the winter are correlated to the mid-winter stratospheric warming, and also seem to connect with some weak and delayed perturbations in the summer simply by observing the progression of the wave amplitudes. The delaying is more clearly depicted at the levels of 2.2 and 1 mb where the peak amplitudes at middle latitudes show up later than those at high latitudes. The amplitude of the (3, 0.5) component grew rapidly at latitudes between 10°S and 50°S during January and the peak amplitude moves poleward at the levels above 0.2 mb from 20°S in early January to 30°S in late January. The amplitude peaks at a slightly lower latitude but moves to a higher latitude as height increases. After a -7 K peak was reached in mid- and late-January at 0,046 mb. the 2-day wave gradually vanished in the summer hemisphere in the beginning of February yielding a duration time of about 40 days for this event.

The horizontal structure of the January 2-day wave matches the characteristics of the (3,0) normal mode showing a node near the equator. In fact, it can be shown later that the perturbations in the two hemispheres are coherent. At the altitudes below 2 mb, the amplitudes are larger in the winter than in the summer possibly because there is a large amount of energy dispersed from the planetary waves in the winter, and this energy may be responsible for the excitation of the 2-day wave eventually. At the altitudes above 2 mb, the amplitude of the summer wave is larger than that in the winter which agrees with the expection for the (3,0) normal mode. It is interesting to note that the enhancement in the summer hemisphere does not immediately follow the first precursor and the actual burst occurred about 10 days later.

The (4, 0.53) component is weaker in amplitude but accountable as a part of the event throughout the month of January (Figure 4). Unlike the (3, O. 5) component, the amplitude of the (4,0.53) component is maximized three times in late December, early January and early February but the amplitude decreased gradually after the first maximum. It is interesting to observe that the first peak was reached earlier than the time when the (3, 0.5) component began to grow, which may suggest some interactions between the two components. A precursor is evident in the winter hemisphere as well at about the same time and place as in the (3, 0.5) component, and shows some connection to the later summer perturbations. The time delay between the summer and the winter perturbations again suggests that the summer 2-day wave may be initially triggered by the winter planetary waves penetrating into the summer.

The latitude-altitude plots (Figure 5) provide clear evidence for the connection between the summer 2-day wave and the winter waves. Day 460 is the time when a strong precursor was observed in the winter hemisphere. The structure of the wave amplitude on this day [Figure 5 (a)] indicates that the winter forcing is radiating away from the polar region to the equatorial area and further into the summer hemisphere. The parallel phase lines in Figure 6 reveal the coherence of the perturbations in the different hemispheres showing a clear out-of-phase relation above 0.2 mb. The out-of-phase relation agrees reasonably well with the expectation of the (3,0) Rossby normal mode. In a realistic atmosphere, the amplitude distribution of the (3,0) mode is symmetric about the equator but largely enhanced in the summer hemisphere (Salby, 1981). Tilted phase lines in Figure 6 suggest that the perturbation is propagating upward and hence energy and momentum may be transported from the winter at low heights into the summer at high altitudes. Coupling to the baroclinic instability above the easterly core, the summer perturbation, in spite of small amplitudes, maybe enhanced rapidly in the unstable region since the unstable waves and the normal mode match in frequency and wavenumber. The similarity of these waves allows the 2-day wave to develop more efficiently in a combined form and become a global oscillation. In studying all the plots after Day 460 we found that the summer perturbation above 0.1 mb was first enhanced and the enhancement at lower altitudes happened later. The plots on Days 483 and 502 show middle steps of the evolution. By the time that the strength of the instability decreases and disappears, as illustrated by Day 526, the winter forcing can no longer excite the 2-day wave in the summer hemisphere although the wave activity is still present in the winter.

The time series of vertical amplitude profiles helps to illustrate the effects of the baroclinic instability in the summer hemisphere. Figure 7 is the time series of the vertical profiles of the (3, 0.5) amplitude at a latitude of 25°S. Two transient forcings, occurring approximately on Days **455** and 467, are related to the first precursor discussed above. The peak amplitudes of the two major forcings are tilted with respect to time, suggesting that these disturbances were propagating upward. These forcings may be crucial to the excitation of the 2-day wave because enhancement is observed following the forcings reach that height level. After the 2-day wave was triggered, the wave amplitude is first enhanced at a higher altitude, and the enhancement progresses downward indicated by the downward tilted contour lines. In other words, the wave is likely to be enhanced effectively in a dynamically unstable region when there is enough energy for disturbances. Such wave development is a manifestation of the baroclinic instability above the summer easterly jet.

The 2-Day Wave in July/August 1993

The morphology of the 2-day wave during this period is not quite a mirror image of what happened in January 1993 for the MLS temperature measurements. As shown in Figures 8 and 9, the events in June/July/August arc generally smaller in amplitude and more sporadic in time. It is known that there is large frequency variability during this period of time, and in the MLS data two prominent components at (3,0.48) and (4,0.53) for zonal waves 4 and 3 are equally important during this period. For the (3, 0.48) component, illustrated in Figure 8, major events occurred on Days 655, 675, 681, 691 and 705. For the (4, 0.53) component in Figure 9, major events occurred less frequently and peaked on Days 662,680 and 705.

During July anti August 1993, the winter wave is weaker than that in January indicated by smaller amplitudes in the winter hemisphere that hardly spread across the equator. However, there are no clear evidence of any precursors or connections between the winter and the summer waves during this period although some variability is exposed in the winter hemisphere. The evolution of the (3, 0.48) component, for example at 0.046 mb, is similar to that in the January event in terms of the poleward movement of the peak amplitude. The evolution of the (4, O. 53) component, however, shows that the movement is poleward during June and July. In August, the peak amplitudes tend to be stablized at a mid-latitude of ~30°N.

It is not yet clear at the present time why the 2-day wave in July/August is weaker than that in January. The phenomenon may be associated with the strength of baroclinic instability or with the amount of energy from the planetary waves leaking into the summer hemisphere. Solutions given by normal mode and instability theories are limited. Normal mode calculations suggest that magnitude of the wave response is proportional to magnitude of the input perturbation but also sensitive to the mean wind structure, while calculations of unstable waves only provide a growth rate during linearly developing period. The MLS observations may suggest that the amplitude of the summer 2-day wave is proportional to amount of energy radiated and dispersed from the winter planetary waves. If this is the case, it is not surprising to observe a weaker 2-day wave in

July/August because the winter wave activity is known to be stronger in the northern than in the southern hemisphere.

Summary and Discussion

Using the latest research algorithms, we are able to retrieve MLS temperature in a broad height range from 46 mb to 0.046 mb and obtain useful information for the 2-day wave study. Observations of the 2-day wave in MLS temperature measurements provide new evidence for excitation and evolution of the transient oscillation. Spectral analysis reveals that there is one major component for the January event and two prominent wave components for the July/August events, consistent with past observations. The 2-day wave in January 1993 appears to be dominated by wave 3 while waves 3 and 4 are both important for the events in July/August 1993.

The wave amplitude and phase structures extracted from the MLS temperature suggest a possible connection between the summer 2-day wave and the winter planetary wave activity. A precursor in the winter hemisphere is found likely as a triggering signature for the summer 2-day wave enhanced in January. The study of the wave evolution suggests that the 2-day wave is possibly affected by both the winter wave forcings and the summer baroclinic instability above the easterly jet. The wave leaking from the winter into the summer hemisphere may be an important triggering forcing, and such forcing can be easily enhanced by the summer baroclinic instability due to the matched frequencies and wavenumbers between the normal and unstable modes. As a combination of the (3,0) normal mode and an unstable wave, the 2-day wave may grow and spread to a wide region in the atmosphere. Randel (1994) also discussed such a possibility of the 2-day wave being a combination of the normal and unstable modes based on a study of 5-year NMC data,. The characteristics of the 2-day wave were found to be mixed with the signatures of the two types of waves and can only be interpreted by the presence of both the normal and unstable modes. The MLS observations show the similar scenario in which the evolution of the 2-day wave contains characteristics mixed with the two types of waves. More importantly, the MLS observations tend to relate the triggering mechanism of the 2-day wave with the forcings in the winter hemisphere, which may help a better understanding of seasonal variation of the wave in the future.

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Figure Captions

Figure 1. Wave spectrum for the period of January 10-30, 1993 at a latitude of 20°S and pressure of 0.46 mb, where the 2-day wave sharply peak at a period of -48 h and wavenumber 3. Contours describe the amplitude responses at each frequency and wavenumber and start from a value of 0.5 K with an increment of 0.5 K. The confident level is -0.5 K for the amplitude response near the 2-day wave.

Figure 2. Wave spectrum for the period of June 18-July 7, 1993 at a latitude of 20"N and pressure of 0.1 mb. Contours start from 0.4 K with an increment of 0.4 K. Two wave components are identified for the 2-day wave event and they are respectively the periods of 50h for wave 3 and 45h for wave 4.

Figure 3. Evolution of the January 2-day wave for the component at (wavenumber, frequency)=(3,0 .5), Contours are labeled from 0.5 K with an increment of 0.5 K. The confident level is estimated to be 0.5 K for most pressure levels from 46 mb to 0.046 mb. The dashed lines show the boundary of MLS sampling which is biased to the different hemispheres alternately as a result of the UARS yaw maneuvers.

Figure 4. As in Figure 3 but for the component (4,0.53).

Figure 5. Latitude-altitude cross section of the 2-day wave amplitude for selected days during the January event. Contours start from 0.5 K at an interval of 0.5 K. A shift of peak amplitude is evident for most of the days, which shows the peak amplitude moving to a higher latitude as the 2-day wave grows into a higher altitude. A burst in the northern hemisphere on day 460 is a strong forcing that maybe able to penetrate into the summer hemisphere to trigger the 2-day wave.

Figure 6. Phase structures of the 2-day wave for the same days as in Figure 5. Plotted are two phase profiles at 20°S (solid lines) and 20°N (dashed lines). The out-of-phase relation is clearly evident when the 2-day wave is significant, which is a good indication of the global presence of the (3,0) Rossby normal mode.

Figure 7. Time series of the 2-day wave amplitude profiles at a latitude of 20°S, showing the upward propagating disturbances in the early time of the event and the downward progression during the major wave enhancement. The upward-and-downward propagation may suggest that the 2-day wave is a combination of the normal and unstable modes.

Figure 8. Evolution of the July/August 2-day wave for the component at (3,0.48). Sporadic events are found throughout approximate two month period between the mid-June and the mid-August. The amplitudes of these events are generally much weaker than the primary event in January 1993.

Figure 9. As in Figure 8 but for the component at (4,0.53). The amplitude response of this component is about twice as large as that of the (3,0.48) component for the most events that happened in this time.